

Charmed Scalar Resonances*

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It is pointed out that assigning $D_{s0}^+(2317)$ to $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$ is favored by experiment. It also is discussed why its neutral and doubly charged partners have never been observed in inclusive e^+e^- annihilation. To search for them, hadronic weak decays of B mesons would be better, and their production rates would be $Br(B_u^+ \rightarrow D^- \hat{F}_I^{++}) \sim Br(B_d^0 \rightarrow \bar{D}^0 \hat{F}_I^0) \sim 10^{-3}$.

The charm-strange scalar meson $D_{s0}^+(2317)$ was discovered in inclusive e^+e^- annihilation [1, 2]. Its mass and width are now compiled as [3], $m_{D_{s0}} = 2317.3 \pm 0.6$ MeV, $\Gamma(D_{s0}^+(2317)) < 4.6$ MeV, CL = 90 %. However, its signal has never been observed in the radiative $D_s^{*+}\gamma$ channel. Therefore, a severe constraint,

$$\mathcal{R}(D_{s0}^+(2317))_{\text{exp}} = \frac{\Gamma(D_{s0}^+(2317) \rightarrow D_s^{*+}\gamma)}{\Gamma(D_{s0}^+(2317) \rightarrow D_s^+\pi^0)} \Big|_{\text{exp}} < 0.059, \quad (1)$$

has been provided [2]. For reference, we here list another data on the ratio [3],

$$\mathcal{R}(D_s^{*+})_{\text{exp}}^{-1} = \frac{\Gamma(D_s^{*+} \rightarrow D_s^+\pi^0)}{\Gamma(D_s^{*+} \rightarrow D_s^+\gamma)} \Big|_{\text{exp}} = 0.062 \pm 0.006. \quad (2)$$

Eq. (2) implies that the isospin non-conserving interaction is much weaker than the electromagnetic interaction. With this in mind, it is learned, from Eq. (1), that the interaction causing the decay in the denominator is much stronger than the electromagnetic interaction, i.e., it is the well-known strong interaction which conserves isospin. Therefore, $D_{s0}^+(2317)$ should be an isospin $I = 1$ state which cannot be realized by the conventional $\{c\bar{s}\}$ but can be realized by a tetra-quark meson, $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$ with $n = u, d$. (Notation of the tetra-quark mesons will be given later.) It is also learned that its $I = 0$ partner $\hat{F}_0^+ \sim [cn][\bar{s}\bar{n}]_{I=0}$ would be observed in the $D_s^{*+}\gamma$ channel.

In addition, charm-strange scalar mesons which are degenerate with $D_{s0}^+(2317)$ have been observed in B decays [4, 5]. In particular, some indications of existence of a charm-strange scalar meson have been observed in the radiative channel [4]. It is quite different from the above $D_{s0}^+(2317)$. Therefore, the charm-strange scalar mesons observed in B decays are denoted by $\tilde{D}_{s0}^+(2317)[\text{observed channel}]$ to distinguish it from the above $D_{s0}^+(2317)$, although $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ will be identified with $D_{s0}^+(2317)$ later.

Regarding charmed non-strange scalar mesons, a broad enhancement (D_0) just below the tensor D_2^* in $D\pi$ mass distribution has been observed [6, 7]. Its mass and width are now compiled as [3]

$$m_{D_0} = 2352 \pm 50 \text{ MeV}, \quad \Gamma(D_0)_{\text{exp}} = 261 \pm 50 \text{ MeV}. \quad (3)$$

To check if D_0 can be interpreted as the scalar $D_0^* \sim \{c\bar{n}\}$ meson, we here study two-body decays of D_0^* (and its strange partner D_{s0}^{*+}) by using a hard pion (or kaon) technique in the infinite momentum frame [8, 9], which is an innovation of the old current algebra. (For the technical details in this article, see references quoted.) In this approximation, the amplitude is given by *asymptotic* matrix element(s) (matrix element(s) taken between single hadron states with infinite momentum) of the axial charge A_π (or A_K). Then, we use asymptotic flavor symmetry (flavor symmetry of asymptotic matrix elements) which is a prescription to treat broken flavor symmetry [9]. Comparing D_0^* and D_{s0}^{*+} with the experimentally known K_0^* [3] which is assigned to the scalar $\{n\bar{s}\}$ [10], and using asymptotic $SU_f(4)$ symmetry [11, 12], we estimate rates for the $D_0^* \rightarrow D\pi$ and $D_{s0}^{*+} \rightarrow (DK)^+$ decays, where the spatial wavefunction overlap is still in the $SU_f(4)$ symmetry limit at this stage. Correcting its deviation (reducing the overlap in open-charm meson decays by $\sim 20 - 30$ % when they are compared with those for light-meson decays [11, 12]) from the $SU_f(4)$ symmetry limit, we obtain $\Gamma(D_0^* \rightarrow D\pi) \sim 40 - 50$ MeV and $\Gamma(D_{s0}^{*+} \rightarrow (DK)^+) \simeq 30 - 40$ MeV, where the mass of D_{s0}^{*+} has been estimated to be $m_{D_{s0}^{*+}} \simeq 2.45$ GeV by using a quark counting with $\Delta_s \simeq m_s - m_n \simeq 100$ MeV and $m_{D_0^*} \simeq 2.35$ GeV in Eq. (3) as the input data. Because the above rates saturate approximately the full widths of D_0^* and D_{s0}^{*+} , their estimated widths [11] are $\Gamma(D_0^*) \simeq 40 - 50$ MeV and $\Gamma(D_{s0}^{*+}) \sim 30 - 40$ MeV. It should be noted that the above $\Gamma(D_0^*)$ is much smaller than $\Gamma(D_0)_{\text{exp}}$ in Eq. (3). Therefore, we expect that D_0 has a structure including D_0^* .

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TABLE I: Rates for radiative decays of charm-strange mesons. Input data are taken from Ref. [3].

Decay	pole	$ \beta_1 ^2$	Decay rate (keV)	Input Data
$D_s^{*+} \rightarrow D_s^+ \gamma$	ϕ, ψ	1	0.4	$\Gamma(\omega \rightarrow \pi^0 \gamma)_{\text{exp}} = 0.734 \pm 0.035 \text{ MeV}$
$D_{s0}^{*+} \rightarrow D_s^{*+} \gamma$	ϕ, ψ	1	15 – 20	$\Gamma(\chi_{c0} \rightarrow \psi \gamma)_{\text{exp}} = 119 \pm 15 \text{ keV}$
$\hat{F}_0^+ \rightarrow D_s^{*+} \gamma$	ω	1/4	2 – 3	$\Gamma(\phi \rightarrow a_0(980) \gamma)_{\text{exp}}$
$\hat{F}_I^+ \rightarrow D_s^{*+} \gamma$	ρ^0	1/4	20 – 25	$= 0.32 \pm 0.03 \text{ keV}$

Four-quark mesons can be classified into the following four groups [13],

$$\{qq\bar{q}\bar{q}\} = [qq][\bar{q}\bar{q}] \oplus (qq)(\bar{q}\bar{q}) \oplus \{(qq)[\bar{q}\bar{q}] \pm [qq](\bar{q}\bar{q})\} \quad (4)$$

with $q = u, d, s$, where parentheses and square brackets denote symmetry and anti-symmetry of flavor wavefunction, respectively, under exchange of flavors between them. Each term on the right-hand-side (r.h.s.) of Eq. (4) is again classified into two classes with $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ and $\mathbf{6}_c \times \bar{\mathbf{6}}_c$ of the color $SU_c(3)$. However, these two states can largely mix with each other in the light tetra-quark mesons while, in the corresponding open-charm mesons, such a mixing would be much smaller, because QCD is non-perturbative at the energy scale of the light meson mass while (rather) perturbative at the energy scale of the open-charm meson mass. Anyway, we here concentrate on the $[qq][\bar{q}\bar{q}]$ mesons. The observed mass hierarchy of low lying scalar nonet mesons, $a_0(980)$, $f_0(980)$, $f_0(600)$ [3] and $\kappa(800)$ [14], and the approximate degeneracy between $a_0(980)$ and $f_0(980)$ can be easily understood by assigning them to the $[qq][\bar{q}\bar{q}]$ mesons [13].

Extension of the above $[qq][\bar{q}\bar{q}]$ mesons to open-charm mesons is straightforward: $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$ and $\hat{F}_0^+ \sim [cn][\bar{s}\bar{n}]_{I=0}$ with $S = 1$; $\hat{D}^+ \sim [cn][\bar{u}\bar{d}]$ and $\hat{D}^s \sim [cs][\bar{n}\bar{s}]$ with $I = 1/2$ and $S = 0$; $\hat{E}^0 \sim [cs][\bar{u}\bar{d}]$ with $S = -1$. However, it should be noted that their color configuration would be very much different from that of the light four-quark mesons, i.e., the former would be dominantly $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ because of the attractive force between two quarks (and two antiquarks) [15]. With this in mind, we assign $D_{s0}^+(2317)$ to \hat{F}_I^+ [16]. The masses of the other members are estimated very crudely as $m_{\hat{D}} \simeq 2.22 \text{ GeV}$, $m_{\hat{D}^s} \simeq 2.42 \text{ GeV}$, $m_{\hat{E}} \simeq 2.32 \text{ GeV}$, by using the above quark counting and taking $m_{\hat{F}_I^+} \simeq 2.32 \text{ MeV}$ as the input data. The observed narrow width of $D_{s0}^+(2317)$ can be understood by a small rate for its dominant decay. It can be understood by a small overlap of color and spin wavefunctions which can be seen by decomposing the four-quark state into a sum of products of quark-antiquark pairs [12, 17]. To see numerically the narrow width, we compare the $\hat{F}_I^+ \rightarrow D_s^+ \pi^0$ decay with the $\hat{\delta}^s \rightarrow \eta \pi$, where $a_0(980)$ has been assigned to $\hat{\delta}^s \sim [ns][\bar{n}\bar{s}]_{I=1}$. However, we should be careful when we compare decays with different energy scales, in particular, the decays of open-charm scalar mesons with those of the light scalar mesons. Using the hard pion technique with the asymptotic $SU_f(4)$ symmetry [8, 9], taking [12, 17] $|\beta_0|^2 = 1/12$ describing the overlap of color and spin wavefunctions in the open-charm meson decays and $\Gamma(\hat{\delta}^s \rightarrow \eta \pi)_{\text{exp}} = 50 - 100 \text{ MeV}$ [3] as the input data, and correcting the $SU_f(4)$ symmetry breaking, we obtain [12, 17] a sufficiently narrow width,

$$\Gamma(\hat{F}_I^+) \simeq \Gamma(\hat{F}_I^+ \rightarrow D_s^+ \pi^0) \sim 2 - 5 \text{ MeV}. \quad (5)$$

In the same way, it is seen [16] that all the scalar $[cq][\bar{q}\bar{q}]$ mesons are narrow.

Now we study radiative decays of D_s^{*+} , D_{s0}^{*+} , \hat{F}_0^+ and \hat{F}_I^+ under the vector meson dominance with the broken $SU_f(4)$ symmetry and the overlap factor [12, 17] ($|\beta_1|^2 = 1/4$) between \hat{F}_I^+ (or \hat{F}_0^+) and two vector mesons, while $|\beta_1|^2 = 1$ in the case of the $\{c\bar{s}\}$ meson decays because their color and spin configuration is unique. The results are listed in TABLE I in which the $SU_f(4)$ symmetry breaking has been corrected. The ratio of the rate for the $\hat{F}_I^+ \rightarrow D_s^{*+} \gamma$ in TABLE I to that for the $\hat{F}_I^+ \rightarrow D_s^+ \pi^0$ in Eq. (5) is

$$\mathcal{R}(\hat{F}_I^+) \simeq (4.5 - 9) \times 10^{-3}, \quad (6)$$

which satisfies well Eq. (1). Therefore, the experiment favors assigning $D_{s0}^+(2317)$ to \hat{F}_I^+ , as expected intuitively.

As usual [18], we assume that isospin non-conserving decays proceed through a tiny π^0 - η mixing, i.e., $\pi_{\text{phys}}^0 \simeq \pi^0 + \epsilon \eta$, ($\epsilon = 0.0105 \pm 0.0013$). The hard pion technique with the π^0 - η mixing and the asymptotic $SU_f(4)$ symmetry lead [12, 17] to the rates listed in TABLE II, where the $SU_f(4)$ symmetry breaking has been corrected. They are

TABLE II: Rates for isospin non-conserving decays of charm-strange mesons. Input data are taken from Ref. [3].

Decay	$ \beta_0 ^2$	Input Data	Decay rate (keV)
$D_s^{*+} \rightarrow D_s^+ \pi^0$	1	$\Gamma(\rho \rightarrow \pi\pi)_{\text{exp}} \simeq 150 \text{ MeV}$	0.025
$D_{s0}^{*+} \rightarrow D_s^+ \pi^0$	1	$\Gamma(K_0^{*0}(1430) \rightarrow K^+ \pi^-)_{\text{exp}} = 182 \pm 24 \text{ MeV}$	0.3
$\hat{F}_0^+ \rightarrow D_s^+ \pi^0$	1/12	$\Gamma(a_0(980) \rightarrow \eta\pi)_{\text{exp}} = 50 - 100 \text{ MeV}$	0.2 - 0.5

much smaller than the rates for the radiative decays of the corresponding parents, as expected intuitively. From the rates in TABLE I and TABLE II, we obtain $\mathcal{R}(D_s^{*+})^{-1} \simeq 0.06$ which reproduces well Eq. (2). This implies that the present approach is sufficiently reliable. On the other hand, our results on $\mathcal{R}(\hat{F}_0^+)$ and $\mathcal{R}(D_{s0}^{*+})$ are much larger than the experimental upper bound. Therefore, assigning $D_{s0}^+(2317)$ to \hat{F}_0^+ or D_{s0}^{*+} should be excluded.

Independently of the above discussions, $\mathcal{R}(D_{s0}^+(2317))$ has been studied by assigning $D_{s0}^+(2317)$ to D_{s0}^{*+} (or the chiral partner of D_s^+). Although some of them [19] provided values of $\mathcal{R}(D_{s0}^{*+})$ smaller than unity in contrary to our intuitive and numerical discussions, these results are still beyond the experimental upper bound. The other results [20] are close to the upper bound of Eq. (1) or satisfy it. However, these theories have taken a large s -quark mass which is incompatible with the heavy c -quark picture and a large $\Gamma(D_{s0}^{*+} \rightarrow D_s^+ \pi^0)$ which leads to a huge $\Gamma(D_0^*)$ beyond $\Gamma(D_0)_{\text{exp}}$ in Eq. (3). The remaining model is a unitarized one [21] in which $D_{s0}^+(2317)$ is assigned to a $\{DK\}_{I=0}$ molecule. In this case, the mechanism to cause the isospin non-conservation is more complicated than the usual one, and the results are strongly dependent on the values of parameters involved. In this model, however, the charm-strange axial-vector meson $D_{s1}^+(2460)$ is interpreted as a $\{D^*K\}$ molecule [22], and its ratio $\mathcal{R}(\{D^*K\})$ of decay rates corresponding to $\mathcal{R}(D_{s0}^+(2317))$ has been postdicted to be $\mathcal{R}(\{D^*K\}) \simeq 0.05$ which is much smaller than the measured [3] $\mathcal{R}(D_{s1}^+(2460))_{\text{exp}} = 0.31 \pm 0.06$. Therefore, all the assignments of $D_{s0}^+(2317)$ to an iso-singlet state should be ruled out.

As seen above, $D_{s0}^+(2317)$ has been successfully assigned to the iso-triplet four-quark meson \hat{F}_I^+ while the other assignments have been ruled out. Therefore, its neutral and doubly charged partners, \hat{F}_I^0 and \hat{F}_I^{++} , should exist. However, they have not yet been observed in inclusive e^+e^- annihilation experiments [23]. Nevertheless, it does not necessarily mean their non-existence, because whether they can be observed or not depends on their production mechanism. With this in mind, we study productions of $\hat{F}_I^{++}, \hat{F}_I^0$ and \hat{F}_I^+ mesons, and discuss why inclusive e^+e^- annihilation experiments [1, 2] have observed $D_{s0}^+(2317)$ but did not observe its neutral and doubly charged partners. To study productions of scalar $[cn][\bar{s}\bar{n}]$ mesons in e^+e^- annihilation and B decays, we draw quark-line diagrams within the minimal $\{q\bar{q}\}$ pair creation [24], because multi- $\{q\bar{q}\}$ pair creation would be suppressed due to the OZI rule. The diagram (a) in FIG. 1 depicts a most probable production of \hat{F}_I^+ (and a suppression of \hat{F}_0^+ production because of a small $\gamma\{n\bar{n}\}_{I=0}$ coupling) in the $e^+e^- \rightarrow c\bar{c}$ annihilation, and the diagrams (b) and (e) describe their productions through B_u^+ and B_d^0 decays. If the production of charm-strange tetra-quark mesons described by the diagram (a) is the main mechanism in the $e^+e^- \rightarrow c\bar{c}$ annihilation, the \hat{F}_I^0 and \hat{F}_I^{++} production will be strongly suppressed, because there is no diagram describing their production. On the other hand, \hat{F}_I^+ has been observed in the $B_u^+ \rightarrow \bar{D}^0(\text{or } \bar{D}^{*0})\hat{F}_I^+$ and $B_d^0 \rightarrow D^-(\text{or } D^{*-})\hat{F}_I^+$ decays, which are depicted by the diagrams (b) and (e), respectively. Productions of \hat{F}_I^{++} and \hat{F}_I^0 are expected in the decay $B_u^+ \rightarrow D^-(\text{or } D^{*-})\hat{F}_I^{++}$ as seen in the diagram (c) and in the decay $B_d^0 \rightarrow \bar{D}^0(\text{or } \bar{D}^{*0})\hat{F}_I^0$ as seen in the diagram (d), respectively, where the diagrams (c) and (d) are equivalent to (b) and (e), respectively, under the isospin symmetry. Therefore, their production rates are expected to be not very far from those of \hat{F}_I^+ , and hence the branching fractions for \hat{F}_I^{++} and \hat{F}_I^0 productions can be estimated as [24] $Br(B_u^+ \rightarrow D^-\hat{F}_I^{++}) \sim Br(B_u^+ \rightarrow \bar{D}^0\hat{F}_I^+)$ and $Br(B_d^0 \rightarrow D^-\hat{F}_I^0) \sim Br(B_d^0 \rightarrow \bar{D}^{*0}\hat{F}_I^+)$.

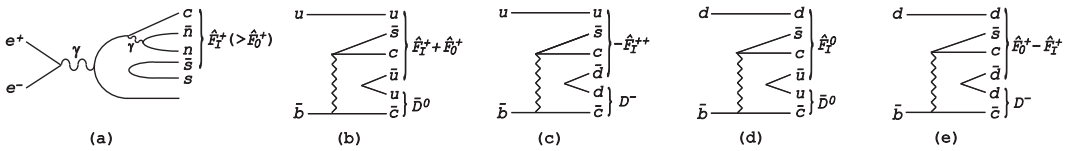


FIG. 1: Production of charm strange mesons in e^+e^- annihilation. (a) depicts a production of \hat{F}_I^+ (and \hat{F}_0^+). (b) and (e) describe productions of \hat{F}_I^+ (and \hat{F}_0^+) through B_u^+ and B_d^0 decays. Productions of \hat{F}_I^{++} and \hat{F}_I^0 through B_u^+ and B_d^0 decays are described by the diagrams (c) and (d), respectively.

$Br(B_d^0 \rightarrow \bar{D}^0 \hat{F}_I^0) \sim Br(B_d^0 \rightarrow D^- \tilde{D}_{s0}^+(2317)[D_s^+ \pi^0])_{\text{Babar}} = (1.8 \pm 0.4 \pm 0.3_{-0.4}^{+0.6}) \times 10^{-3}$, where the last equalities have been taken from Ref. [5].

In summary, we have studied co-existence of the open-charm conventional and tetra-quark scalar mesons. As for the former, the estimated widths are $\Gamma(D_{s0}^{*+}) \sim 30 - 40$ MeV and $\Gamma(D_0^*) \sim 40 - 50$ MeV which is much narrower than that of the measured broad $D\pi$ enhancement.

Because the observed scalar nonet mesons, $a_0(980)$, $f_0(980)$, $f_0(600)$ and $\kappa(800)$, can be well understood by the $[qq][\bar{q}\bar{q}]$ mesons, they have been extended to open-charm system, and $D_{s0}^+(2317)$ has been successfully assigned to \hat{F}_I^+ . It has also been discussed that all the members of the scalar $[cq][\bar{q}\bar{q}]$ mesons are narrow. Therefore, it is awaited that experiments re-analyze more precisely the observed enhancement (D_0) just below D_2^* in the $D\pi$ mass distribution, and find its structure including D_0^* and \hat{D} .

Next, it has been demonstrated that the ratio of the decay rates, $\mathcal{R}(\hat{F}_I^+)$, satisfies well the experimental constraint, while $\mathcal{R}(\hat{F}_0^+)$ and $\mathcal{R}(D_{s0}^{*+})$ are far beyond the experimental upper bound. In this way, it has been concluded that $D_{s0}^+(2317)$ should be assigned to \hat{F}_I^+ but its assignments to D_{s0}^{*+} and \hat{F}_0^+ should be ruled out. The other existing theories which have postdicted $\mathcal{R}(D_{s0}^+(2317))$ are critically reviewed. The above discussion implies that \hat{F}_I^0 and \hat{F}_I^{++} should exist. It has been argued that B decays would be better to search for \hat{F}_I^0 and \hat{F}_I^{++} than inclusive $e^+e^- \rightarrow c\bar{c}$ annihilation, and their production rates are expected to be $Br(B_u^+ \rightarrow D^- \hat{F}_I^{++}) \sim Br(B_d^0 \rightarrow \bar{D}^0 \hat{F}_I^0) \sim 10^{-3}$.

It is awaited that experiments will confirm co-existence of the conventional and tetra-quark mesons in near future.

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